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NATURAL SLOPE STABILITY AS ELATED TO GEOLOGY, AN CLEMENTE AREA, ORANGE AND AN DIEGO COUNTIES, CALIFORNIA

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SPECIAL REPORT 98
California Division of Mines and Geology
Ferry Building, San Francisco, 1968

FRONT AND BACK COVERS: Recent landslide in the City of San Clemente, Orange County

NATURAL SLOPE STABILITY AS RELATED TO GEOLOGY, SAN CLEMENTE AREA, ORANGE AND SAN DIEGO COUNTIES, CALIFORNIA

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ABSTRACT

Urbanization in southern California has extended from relatively flat-lying areas into the highlands where geologic features and processes significantly affect the stability of the surface and cost of engineering works. The San Clemente area lies in the path of urban development in the low rolling hills inland from the coast near the Orange County-San Diego County boundary.

The most widely distributed rocks in the San Clemente area are shale and mudstone of the Monterey Formation of middle and late Miocene age, and mudstone of the Capistrano Formation of late Miocene to early Pliocene age. These rocks are separated in the northeast corner of the area from sandstone of the Santiago Formation of Eocene age by the northwest-trending Cristianitos fault. Along the coast an extensive marine terrace was developed, probably during Pleistocene time, on which has been built most of the City of San Clemente.

An unusual combination of adverse geologic features and processes has led to widespread landsliding in this area. Analysis of the origin of the landslides, which can be traced to rock type and structural and geomorphic factors, provides a means of predicting the natural stability of all slopes. The rock type is the principal factor of control of slope stability, and this factor varies with the relative gross strength of the various formational units. Structural elements that affect slope stability are regional uplift of the continental shelf, faulting, differential erosion along fault-line scarps, and possibly jointing. The principal geomorphic factors are slope angle, the configuration of the stream courses, the geometric relationship between stream courses, differential erosion between and within formations, ancient marine erosion, and the landslide process. All of these controlling factors have been integrated and displayed on a single map which shows the general range of natural slope stability throughout the area. This map is intended for broad scale terrain evaluation and not for the planning of specific engineering projects.

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NATURAL SLOPE STABILITY AS RELATED TO GEOLOGY, SAN CLEMENTE AREA, ORANGE AND SAN DIEGO COUNTIES, CALIFORNIA

BY ROBERT P. BLANC AND GEORGE B. CLEVELAND

INTRODUCTION

California, unlike some maritime regions, has a narrow and discontinuous coastal plain in contrast to the length of its coastline. The most extensive segment of this plain lies in southern California between Los Angeles and Mexico. It is within this region that the greatest concentration of California's population has settled, with the main loci of urban growth at Los Angeles and San Diego. These centers merge with other communities and form an urban complex which has inundated much of the lowland areas. Although urbanization has expanded principally from north to south within the coastal plain, a significant part of the growth has developed radially from the population centers into the highlands.

This transition from flatland to hillside development has helped lead to a greater awareness of geologic elements—processes and features—that influence the stability of the ground and cost of engineering structures. These geologic elements are dormant below terrains of low relief, but on the hillsides they present potential problems that are contained only through careful geologic study and good engineering practice. An understanding of these elements is therefore a sound economic consideration and an integral part of orderly hillside development.

The San Clemente area, in the west half of the U. S. Geological Survey San Clemente 7½-minute quadrangle, lies partly along the coast and straddles the boundary between the narrow coastal plain (marine terraces) and a rolling highland to the north (fig. 1). The City of San Clemente was developed mainly on flat-lying marine terraces but in recent years the hillsides have been more extensively utilized. The hillsides are mantled with numerous landslides.

This study was initiated to evaluate the stability of natural slopes by determining the causes of landslides, and to present the data on natural slope stability in a form readily usable for broad scale urban planning. This report does not attempt to evaluate the stability of artificially cut slopes, terraced pads, or fills that have previously been made in or placed on the bedrock, or the stability of any future excavations or artificially made ground.

Dr. Donald Carlisle of the University of California, Los Angeles and Rudolph G. Strand of the California Division of Mines and Geology, kindly criticized the manuscript, but neither must be considered an accomplice in this venture. The authors acknowledge the cooperation of the Richfield Oil Corporation in releasing paleontological and other data.

SLOPE STABILITY

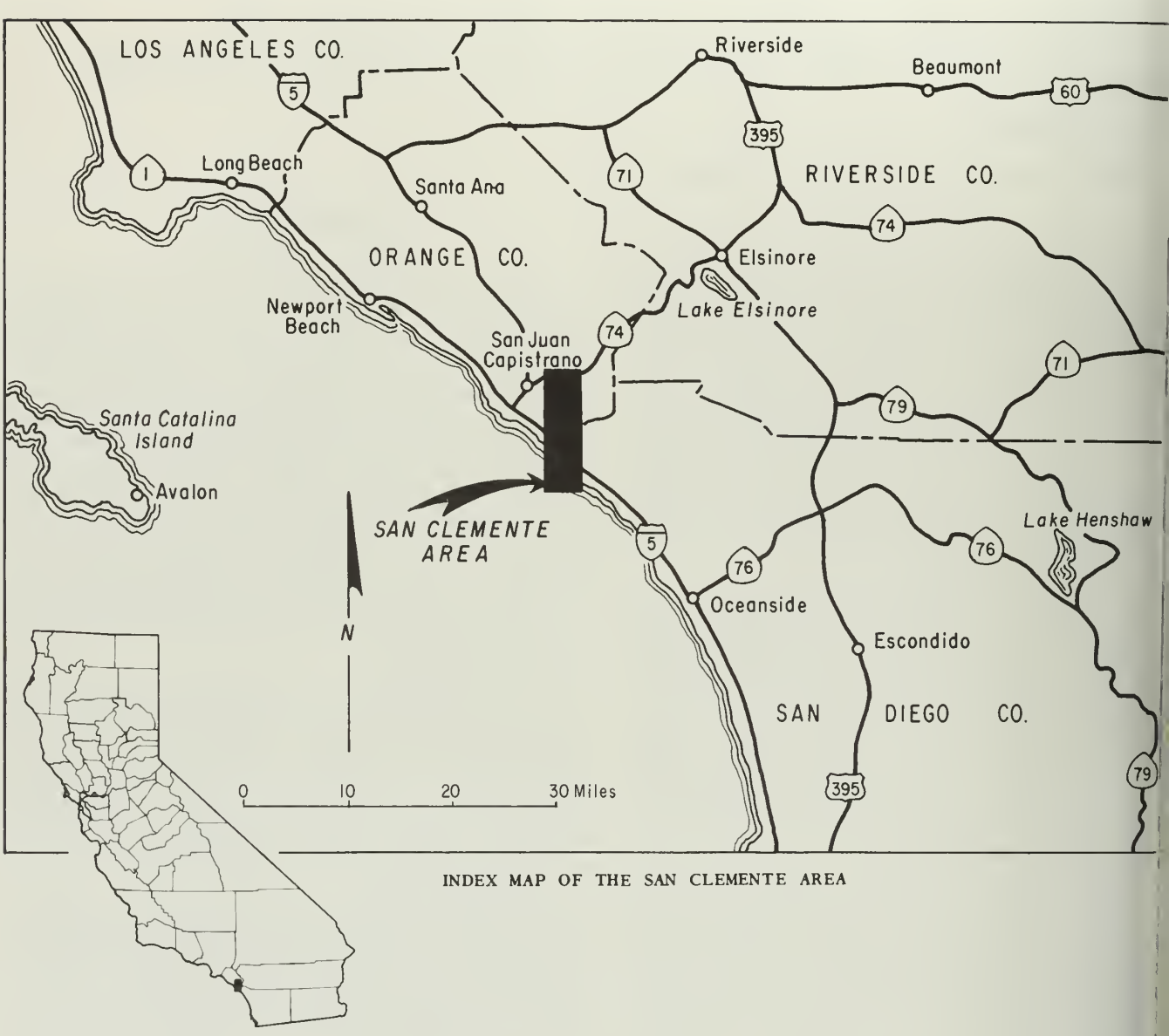
General considerations

The lithologic framework of an area is a basic consideration in assessing slope stability. However, within this framework the influence of structure and geomorphic processes, among other factors, bears on the strength and behavior of the rocks. Locally, they can exercise a greater influence than the inherent properties of the rocks themselves. From the interrelationship of all of the geologic factors emerges a continuity unique to a geologic province. An appreciation for this continuity provides a means for predicting the behavior of rocks throughout the province. Furthermore, it forms a useful lattice within which details collected for site studies can be fitted. Without such a regional reference datum, local site data may lack a fundamental geologic basis and may lead to unwarranted conclusions.

Moreover, the geologic continuity in a province may be expressed in the morphologic pattern of the landscape. The slopes may weather and erode in a predictable manner and the slope angles lie within a definite range, all leading to a general homogeneity in the landforms. An appreciation for this morphologic pattern in a given province is useful in analyzing general slope stability and in recognizing both recent and ancient landslides.

Landslides, unlike most geologic features, develop within relatively short periods of time. During normal slope retreat, weathering and erosion proceed slowly and uniformly and the general appearance of the landscape is preserved. Physiographic continuity extends over wide areas. But landsliding accelerates mass wasting, and landslide features commonly stand out in sharp contrast against the uniform appearance of the surrounding country. The contrast is most apparent at the time of sliding and gradually becomes less apparent as the landscape is remolded by weathering and erosion.

The evidence for recognizing landslides, too, passes from the sharp morphologic features of youthful slides to indirect geologic relationships which may be the only clues left to indicate ancient landslides. Therefore, the principal means of recognizing landslides, especially for ancient slides, depends on an orderly survey of the geology. Once the geologic setting is known for a given area, and the normal response of each rock type to weathering and erosion is established, the features that indicate landsliding become more readily apparent. Furthermore, seldom can any one criterion be relied upon as proof of sliding: the older the landslide the less direct and apparent the evidence for it, and the greater the need for a number of criteria to substantiate its presence.



INDEX MAP OF THE SAN CLEMENTE AREA

Figure 1.

Landslides in the San Clemente area

The San Clemente area is underlain mainly by incompetent sedimentary rocks which have been molded by stream erosion and weathering into low rounded hills. Landslides are common throughout the area southwest of the Cristianitos fault, but the widespread landslide terrain terminates abruptly at the fault. The fault cuts across the northeastern corner of the area, with older rocks of greater stability to the northeast (pl. 1).

Near the ocean, marine erosion has formed a broad wave-cut terrace extending back from the coastline and several tens of feet above sea level. This relatively flat-lying surface is cut mainly in rocks of the Capistrano Formation and is mantled with poorly consolidated marine terrace sands and a non-marine alluvial cover. Although these rocks, which are e posed in the sea cliffs and in the steep canyons th cut back from the coast, are all relatively weak, t terraced part of the area is not marked by extensi landslides. Not only does the capping of marine a non-marine deposits help protect the underlying a relatively unstable bedrock, but stream erosion is r significantly active and a broad beach protects the cliffs from wave action.

Cristianitos and San Mateo Creeks, which form p of the eastern boundary of the mapped area, are t principal drainage courses for a broad region no and east of San Clemente. Their relatively large s and location with respect to the various geologic f mations have been responsible for large scale landsl ing, as has the San Juan Creek drainage at the north boundary of the area.

Photo 1. View east of bowl-shaped landslide terrane along east border of sections 27 and 34. Major landslide shown in middle center, and subsidiary slides slipping toward main mass off slopes from the north and south. Development of bowl-like depressions is initiated by spur failures at the confluence of two stream courses. Bowls commonly merge leaving undisturbed a high prominence or a sinuous ridge with an apron of landslides on each side.

The landslides in the San Clemente area are mainly bedrock failures. Because of the largely incompetent nature of the rocks involved, the landslide debris is generally reduced to relatively small blocks. The piles of landslide debris are somewhat rounded and the material has the appearance of having flowed or tumbled. Although much of the area is mantled with slope wash and other types of surficial deposits, these materials seldom fail except where bedrock formations fail beneath them. Slope wash accumulations of more than a few feet thick are subject to creep. Locally creep and landsliding have furnished debris to the stream courses faster than it can be transported away from any point by stream erosion, so broad flat-bottomed valleys have developed.

The landslides in the map area occur mainly along the slopes of stream courses as discrete units or as aprons of coalescing slides. An example of a well developed apron of slide debris is the one along the northwest side of the unnamed stream course in section 27, where the canyon slope has failed at several places due to stream downcutting and undercutting. Locally, sliding at the nose and along the margins of low-lying interfluves has developed broad debris-choked amphitheater-shaped depressions. The terrain consists of numerous individual slides slipping off the bounding slopes of the depression and flowing down toward the center to coalesce in a composite slide. The individual slides occurring along the margins are rotated ultimately in the direction of movement of the main composite slide mass. In the main direction of sliding the depression narrows, in the form of an inverted tear drop, and stream erosion advances principally from the constriction headward around the periphery of the main slide mass. This promotes the undercutting of the slide-bounding slopes, enlarging the depression outwardly (photo 1). Locally this process has advanced to the degree where several adjacent depressions have merged leaving only a central core of undisturbed rock with slide terrain on nearly all sides. Although the terrain is much more subdued, it is somewhat analogous in general form to areas where continued glacial erosion has cut deeply around the slopes of a mountain, leaving only the highest prominence, or horn (photo 2). Where the process has not reached such a high degree of development, long sinuous walls ("aretes") of stable rock can be traced through a sea of landslide debris. Good examples of these features occur in the southwest quarter of section 21 and the northeast quarter of section 34.

Photo 2. View north of landslide terrane in southeast part of section 28, showing several generations of landslides in middleground. Promine bed cropping out below power pole lies near the base of an undisturbed core with landslides nearly all around the sides of the hill.

Landslides in the map area range in size from less than an acre to more than a square mile. The size of most landslides is controlled by the size of the downslope area into which the debris must slide. Landslides formed in the sides of tributary canyons are commonly buttressed by flowing against the opposite wall of the canyon and large scale sliding is prevented. On the other hand, larger drainage courses, like Cristianitos-San Mateo or San Juan Creeks, will accommodate greater volumes of debris, and correspondingly larger landslides have developed along their slopes.

Landslides, while being ephemeral features of the landscape, can nevertheless be preserved for thousands of years if local geologic conditions and climate are favorable. The landslides in the San Clemente area probably represent the cumulative product of slope failure over an extended period of geologic time. No absolute dates have been obtained from materials enclosed in landslide debris from this area, and only the most meager evidence of age is available to give the general range of the geologic age of the landslides.

The oldest direct evidence of age of landsliding is along the San Juan and Cristianitos-San Mateo drainages where stream terrace deposits of Quaternary age lie undisturbed on landslide debris (photo 3). These terrace remnants occur as much as 100 feet above the present flood plain of San Juan Creek, and about 60 feet above the Cristianitos-San Mateo drainage level. While these isolated deposits cannot be given reliable absolute ages, they probably originated when sea lev stood much higher in relation to the land than it do at present, and when these drainage courses were bein aggraded at that higher elevation.

Some of the landslides along the sea cliffs at Sa Clemente have lost much of their morphologic expre sion and appear to be ancient features, whereas fresh looking slides have developed along the walls of th stream courses nearby. The older slides may hav occurred when sea level was slightly higher in relatio to the land, and the cliffs were being eroded by wav action. The lowest recognized marine terrace deposi now are found about 80 to 100 feet above sea leve Elsewhere along the southern California coast, terrac at this general level have been dated from several te to somewhat over a hundred thousand years o (Yerkes and Wentworth, 1965, p. 38; Jahns and Clev land, unpublished manuscript). Therefore, the old landslides that occur along the San Clemente sea clif probably developed after the sea level dropped fro the lowermost recognized marine terrace, but befo it reached its present stand, some distance seawa from the cliffs.

Landsliding is now active in the San Clemente are as shown by the disturbance of short-lived vegetatio growing on the slopes of some landslides. San Cl mente City records indicate that failures have occurr within recent years (Eugene Ayer, personal commur cation, 1962).

From their relationship to terraces, landslides in the San Clemente area appear to range in time of probable origin, from a few thousand years ago—perhaps from tens of thousands of years ago—to the present time.

Origin

The original causes of landslides in the San Clemente area include both primary and secondary factors. The primary factors are related to the inherent characteristics of the rocks and the structural arrangement of the rocks with respect to the landforms. The secondary factors are mainly geomorphic processes, principally modern stream and ancient marine erosion. The primary factors that affect landsliding are static, whereas the secondary factors are largely dynamic.

Landslides that retain a morphologic expression are products of the relatively recent geologic past. They owe their origin mainly to the effects of presently active geologic processes working against a rock and structural framework whose weaknesses are largely inherent. Furthermore these processes, mainly stream erosion and weathering, are greatly affected by climate. Moreover, each factor can have a wide range of influence on slope stability depending on the degree to which it is developed locally. For example, stream erosion may need to be vigorous to undercut a slope and cause a landslide in competent rocks, whereas relatively minor stream erosion may cause a landslide in a slope developed on weak rocks. Hence, an involved relationship apparently exists between all of the factors.

In order to evaluate the factors affecting the stability of slopes in the San Clemente area, a method of identifying and analyzing each one separately is necessary. Then, the desired total or net stability of all slopes throughout the area can be estimated, and expressed in terms of relative propensity to slide. These stability factors have been grouped and analyzed under the headings rock type, structure, and geomorphology. Although climate and geologic history are extremely important, acting through the geologic past to affect present-day stability conditions, they are constant for the relatively small San Clemente area. Seismic shocks would certainly affect the stability of slopes in the San Clemente area, but little data is available to measure the influence of potential earthquakes on these rocks.

Rock type. Slope stability is strongly influenced by such rock properties as cementation, grain size and shape, porosity, and fabric of the rock itself. The collective effect of these rock properties can be expressed generally as the gross strength of the rock, which is seen mainly as the resistance of the rock to degradation. Most formations are groups of rocks of similar type and properties. Further, different formations can be grouped together according to the general strength characteristics of their typical rocks. The properties of the rocks of the various formations in the San Clemente area have been contrasted with each other by observing and comparing their behavior in the field. Since the determination of their strength characteristics is not everywhere sufficiently precise to rate them in meaningful order, some further grouping and explanation is necessary.

Formations with similar gross rock strength characteristics have been grouped so as to subdivide the rocks of the San Clemente area into four strength units based largely on lithology:

Group I	Landslide deposits
Group II	Capistrano Formation; Monterey Formation
Group III	San Onofre Breccia; Topanga Formation; Vaqueros and Sespe Formations; Santiago Formation
Group IV	Alluvium, beach sand and pond deposits; stream terrace deposits; non-marine terrace deposits; marine terrace deposits and San Mateo Formation

Landslide deposits, group I, generally comprise the weakest materials in the area. These deposits have developed through tumbling, fracturing, and mixing of various types of parent rocks, resulting in largely unconsolidated material. Locally, landslide deposits may

Phata 3. View west across Cristianitos Creek toward ancient landslide terrane. Landslide extends fram ridge an skyline dawn ta creek battam in egraund; hill in right middlegraund is undisturbed. Landslide is a composite af several individual units in variaus stages of equilibrium. In left ddlegraund landslide debris has been averlain by stream terrace deposits and subsequently a yauthful drainage has develaped an it. Slide debris center middleground shaws evidence af recent mavement.

have retained much of the character of the original rock and occur as relatively large rotated but coherent blocks. Commonly these blocks are recently calved off units near the heads of slides. Therefore, landslide debris can have a wide range of physical properties, but all of these materials have been grouped together as landslide deposits because generally the original rock has lost much of its inherent strength through the landslide process.

The Capistrano and Monterey Formations are considered together in strength group II, although they possess some differences in inherent strength. The Capistrano Formation, although largely a mudstone, contains some sandy separations and locally is incipiently bedded. The sandy layers, which are largely lenses, occur mainly near the base, but also from place to place throughout the vertical extent of the formation. The sandstones near the base are poorly cemented and subject to rill wash, whereas elsewhere in the section, sandstone partings add considerable strength to the mudstone and tend to stabilize slopes where they are present. The weak bedding, where developed, does not appear to affect the strength of the formation.

The Monterey Formation is largely thin-bedded shale and mudstone; the platy siliceous shales common to the formation elsewhere were not seen in the San Clemente area. A transition zone, about 200 feet thick, between typical Monterey and typical Capistrano rocks is particularly subject to landsliding. It is within this zone that the strength characteristics of the two formations are most nearly the same. The transition zone is characterized by thin-bedded gray to buff siltstone and shale which near the base is interbedded with white diatomaceous shale generally less than two feet thick. A marker bed of buff-colored siliceous sandstone occurs near the top of the zone. It weathers to small, light-colored chips which stand out on the slopes against the dark-colored soil. The lower part of the Monterey Formation is more diatomaceous and appears less prone to sliding—a relationship noted also in the Palos Verdes Hills, Los Angeles County (Jahns and Cleveland, unpublished manuscript).

The San Onofre Breccia, Topanga Formation, Vaqueros and Sespe Formations, and Santiago Formation comprise strength group III. The wide range of possible lithologic types represented by this group would seem to offer more differences than similarities. However, excepting the San Onofre Breccia, which is largely composed of coarse-grained and angular shaped clasts, the formations consist mainly of sandstone. Furthermore, these rocks fall into a natural grouping because of the dissimilarity between their gross strengths and the strengths of the rocks of groups II and IV, which they lie between. With the exception of the Santiago Formation, the formations in group III are limited in distribution and their strength characteristics are the least understood. It is doubtful if the San Onofre Breccia would be as prone to slide in this area from its rock strength properties alone, if certain structural relationships were not also a part of its local geologic settting. The Vaqueros and Sespe Formations also appear to be somewhat misplaced in this group, inasmuch as they are not known to slide. But because these formations are recognized in only a very limited part of the San Clemente area, providing only very meager samples of their strengths, they were placed in this group along with the Santiago Formation because they most closely resemble it in physical properties. The Santiago Formation, being a coarse-grained and for the most part poorly cemented rock, disintegrates intergranularly and only locally does it fail in massive units.

The lithologic units that comprise strength group IV, and that are not known to landslide, include alluvium, beach sand, pond deposits, stream terrace deposits, non-marine terrace deposits, marine terrace deposits and the San Mateo Formation. The gross strength of the rocks in group IV is much less important a factor in their non-landsliding behavior than with the other groups. The effects of topography, degree of consolidation, freedom from erosion, and thickness, are much more important determinants of their stability behavior. These units are stable for largely unrelated reasons. Alluvium, beach sand, pond deposits, and stream terrace deposits are not subject to massive landsliding because they are distributed in low lying areas, because they are deposits being formed at the present time and thus not generally subjected to simultaneous erosion, and because they form only relatively thin cover on the bedrock. The remaining units, although they are soft and largely incompetent apparently are involved in sliding only when underlying formations fail. Moreover, the non-marine and marine terrace deposits are so thin compared to the other formations, that sliding other than minor sloughing is largely eliminated. The San Mateo Formation is surprisingly stable along the coast where an extensive palisade has been cut into it by marine erosion (photo 4). Elsewhere, at higher elevations San Mateo rocks are found as landslide debris, but only where the Capistrano Formation is known to lie at shallow depth below them. The cementing material in the San Mateo rocks appears to weather away readily, freeing a constant flow of sand grains down slope; it does not fail in massive blocks, or flow because of groundwater saturation, as is common with finer-grained rocks. In this respect the San Mateo Formation is similar to the Santiago Formation, from which it probably was derived (photo 5).

The distribution of the four groups of rocks described above is shown on figure 2. This illustration summarizes the slope stability of the San Clemente area, with respect to the influence of rock strength.

Structure. Structural elements present in the rocks of the San Clemente area include intergranular and hand-specimen scale structures, general uplift, faulting, jointing, and shearing; only minor folding is seen in the area. The influence on slope stability attributable to structural features in sedimentary rocks, whether they be primary and part of the original fabric of the rock, or induced effects related to the tectonic history of the rock, can be related to intergranular strength. The greater this strength, the more pronounced are the effects of structural features. In the main, these structural features tend to weaken the rock. Structure tends to manifest itself mainly in planar elements; the

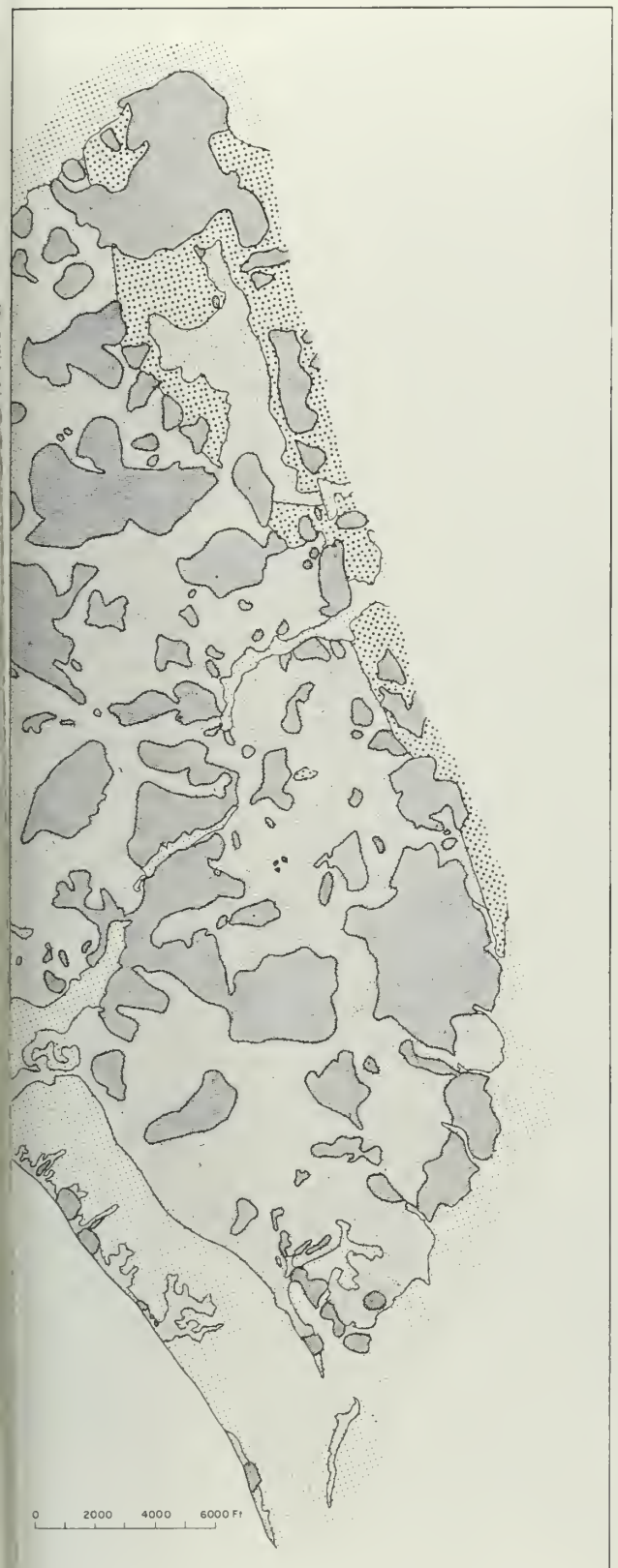
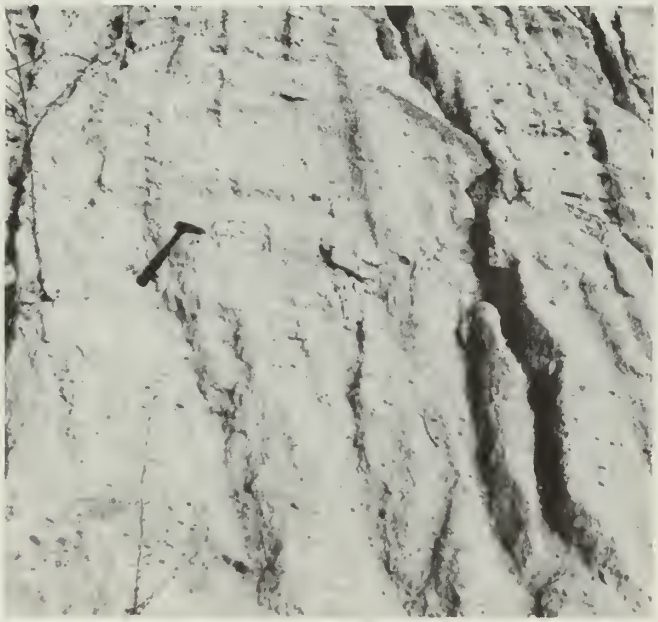


Figure 2. Lithalogic graups related to slape stability in the San emente areo. The several formations have been collected into four oups based an the relative grass strength af the rocks. Relative engths is shawn by the density af the pattern; the dorker the pattern, mare prone ore the racks to fail. These dato were used in the con- uction af the Slope Stability Map (pl. 1).

Phata 4. View sautheast along coast in City of Son Clemente, shawing resistant sandstane beds of Son Mateo Formotion.

planes are commonly surfaces of weakness in the rock.

If the intergranular strength of the rock is less than the effects of any structural weakness, structure does not significantly control the total strength of the rock or its propensity to slide. In the San Clemente area, the most widespread rocks, those of the Capistrano and Monterey Formations, with a few notable exceptions, are inherently too weak to be significantly affected by structural elements.



Phata 5. Outcrap of coorse, paorly sorted sandstone of Son Mateo Farmatian shawing clasts af mudstone af the Capistrano Formotian (right of hammer). Evidence in San Clemente area suggests rock is a turbidite.

Perhaps the most widespread structural influence on landsliding in the San Clemente area, and possibly from place to place along much of the California coast, is the gradual uplift of the continental shelf during Quaternary time. This uplift led to more rapid downcutting and undercutting of slopes by stream erosion, in turn leading subsequently to landsliding. The effect of the elevation of the land above sea level was interrupted at different times during the Pleistocene by the accumulation and wasting away of continental ice masses which led to periodic lowering and raising of sea level. The magnitude of total uplift is indicated by marine terraces preserved more than a thousand feet above present sea level in the southern California area; only about 300 feet of this change can be ascribed to eustatic fluctuation.

Emery (1960, p. 20) suggests that a world-wide eustatic lowering of sea level about 3000 years ago, noted by several workers, may have isolated the modern sea cliffs from wave erosion along the Palos Verdes Peninsula in Los Angeles County. This event may account also for the well-preserved sea cliffs at San Clemente. Subsequently, nearshore marine processes have built a broad beach further protecting the cliffs from the sea.

Faulting has indirectly, though strongly, influenced landsliding locally, by bringing unstable rocks into juxtaposition with relatively more stable, but more easily eroded rocks. For example, the Cristianitos fault is indirectly responsible for landslides of the San Onofre Breccia that cross the fault in the area directly south of San Juan Creek. The rocks of the Santiago Formation on the northeast side of the fault have been eroded more extensively than the San Onofre Breccia on the southwest side, creating a fault-line scarp, and removing lateral support from the San Onofre Breccia, which subsequently failed. A similar relationship exists along the southwest side of the Forster fault in the same general area, where the Capistrano Formation has been faulted against the San Onofre Breccia and subsequent erosion of the Capistrano away from the fault has left slopes in the San Onofre Breccia oversteepened and prone to sliding (fig. 3).

Jointing is the only small-scale structural feature that can be related to landsliding with any consistency. Joints are well developed locally in the Monterey and Capistrano Formations, and may be the primary planes of shearing or failure on which many of the landslides have originated. However, the joint planes observed in these rocks appear to be developed only incipiently, and it seems unlikely that they are invariably the weakest planes in these rocks. Locally, however, it can be demonstrated that on steep slopes joint planes control a general shedding of relatively minor blocks near the slope surface (photo 6).

The reputation of the Monterey Formation elsewhere for failing along bedding planes makes it likely that some of the landslides in the San Clemente area owe their origin to this type of failure, even though this could not be demonstrated with the exposures which were available.

Geomorphology. The geomorphic factors of most significance in predicting natural slope stability in the San Clemente area are related to the configuration of the stream courses, the slope angle, differential erosion between and within formations, ancient marine erosion and the landslide process.

The stream courses have developed in a dendritic pattern. The density and configuration of the pattern is nearly uniform throughout the area, and only in the landslide terrain are the drainage courses relatively more widely spaced and less extensively developed. Normal erosional downcutting and undercutting have removed support from canyon slopes and led to numerous landslides. The sinuous traces of the streams lead to undercutting of projecting slopes in the stream channels and to minor sloughing off of small blocks. Eventually the removal of more and more material leads to major failures along the slopes (photo 7). Failure of a spur between converging streams also is common and can be attributed to the removal of support on two sides of a roughly triangular block near the confluence of the two stream courses.

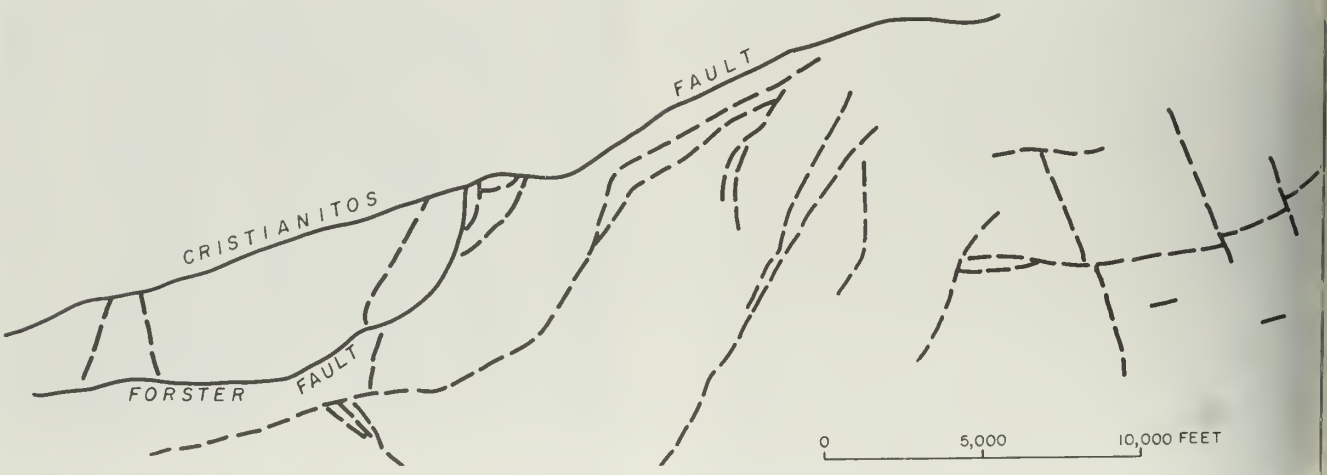


Figure 3. Fault pattern in the Son Clemente area. The develapment of fault line scarps along the Cristianitos and Farster faults has led to concentration of landslides alang their troces. Other faults, shown as dashed lines, may have same influence on slope stability. The traces af the Cristianitas and Forster faults were used in the constructian of the Slape Stability Map (pl. 1).

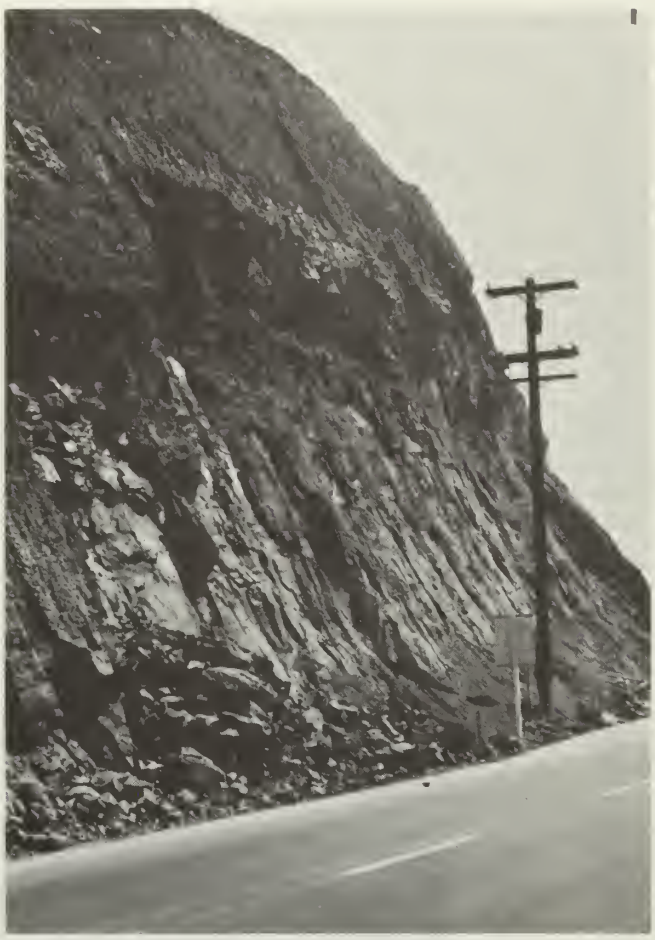


Photo 6. Artificially cut slope in Capistrono Formation on coast near Capistrano Beach about 3½ miles northwest of San Clemente orea. Bedding planes dip gently into slope that is foiling olong a well developed joint system nearly normal to bedding. Massive londsliding is not evident anywhere along cut, but frequent minor foilures pose a road maintenance problem.

hoto 7. Landslide terrane near southeast corner of section 3 T9S, R7W, SMB. View north of landslide in middleground that moved from east west, blocking moin canyon in center background. Ponded droinoge spilled over low divide to west and established new stream course to the s on marine terrace.

Whatever the means by which slopes are steepened, when they reach a critical angle in relation to the strength of the materials involved, failures can occur. This critical slope angle is somewhat different for each formation in the area; moreover, each formation ranges in strength depending, among other local considerations, on the degree of groundwater saturation and degree of weathering. A general appraisal, both in the field and from the topographic map, of the slopes on which landslides occur, especially those developed on the Monterey and Capistrano Formations, suggests that a slope angle of about 10 degrees is critical (photo 8). This critical angle is undoubtedly influenced by jointing or other variables in the bulk strength of the rock involved. However, as a general concept and applied in not too arbitrary a manner, it may be useful in appraising the stability of slopes in the San Clemente area. In evaluating slopes on the San Onofre Breccia and on the San Mateo Formation the 10 degree angle does not apply in some localities where both of these rock units exhibit relatively greater strengths than their overall general strengths throughout the area.

time. The cliffs are steep and relatively free of de bris at the base, much like the cliffs being forme by marine erosion directly south of San Clemente nea San Onofre, but unlike the more gradual slopes of th ancient sea cliffs at higher elevations. Relatively sma landslides occur along the modern sea cliffs and appea to be mainly products of the over-steepened slope. The sea cliffs in this area are now protected fror marine erosion by an elevated right-of-way of th Santa Fe Railroad and a relatively broad beach.

Marine erosion has contributed to landsliding abov the inland edge of the main terrace surface along a ancient sea cliff from 100 to 200 feet high, probabl of late Pleistocene age. Although this cliff has bee modified by subsequent erosion and by artificial agen cies, it forms a bold front which has failed locall because of its over-steepened slope. Evidence of rel tively ancient as well as probably recent sliding found from place to place along the cliff. The cli is cut mainly in the rocks of the Capistrano Form tion except locally along the southeastern part whe the San Mateo Formation is exposed. The landslid

Photo 8. View west of landslide in northwest quarter of section 22, on shallow slope in shales of the Monterey Formation. Landslide is mainly of slump type, but locally debris has the appearance of having flowed.

Differential erosion has occurred on slopes cut in dissimilar formational units, leading to undermining and slope failure. Landslides occur on slopes cut in the San Mateo Formation overlying the Capistrano Formation, and on slopes cut in marine terrace deposits overlying the Capistrano Formation. In each case the underlying Capistrano rocks eroded away more readily, removing support from the overlying rocks, which then failed by landsliding. Locally, within a single formation, the removal of support below competent beds has led to failures, as in the Monterey Formation where massive sandstone beds have failed above more easily weathered shales.

Marine erosion formed the cliffs along the present coastline probably in late Pleistocene or early Recent

are confined entirely to the Capistrano Formation can be ascribed to the undermining effect of remov of Capistrano rocks that underlie the San Mateo Fo mation.

At the head of any landslide, the scar along whi movement took place represents the interface betwe that part of a slope which was stable and that pa which was unstable. If the rocks up slope above t landslide had been but a little weaker, they wou have failed as well, and the landslide would be co respondingly larger. Moreover, the conditions whi precipitate landsliding, mainly the removal of suppo may be only temporarily contained by the shiftin downward of the slide debris onto the lower part

the slope. This is especially true if the debris is deposited across an active stream course where it is subjected to vigorous erosion. The erosion of debris at the toe of the landslide removes support from the main slide mass and continues its development. The natural slope above the slide and especially that part adjacent to the head of the slide is seldom left in any but the most tenuous state of stability. The scarp directly below the head is generally much steeper than the natural slope that failed originally. Therefore a self-perpetuating process develops, of headward advancement and general enlargement of the landslide. Thus the undisturbed slopes above landslides in the San Clemente area, as well as elsewhere, are generally places of special concern in evaluating possible future slope failure.

The geomorphic map, figure 4, designates those slopes that are at or above critical angles. It also shows the distribution of the stream courses along which failures are prone to occur in the adjacent slopes. Furthermore, it shows the interfluve at the confluence of two stream channels where these points appear to be particularly unstable. The most recently active landslides are still in a stage of development, and further headward advancement could endanger the stability of slopes above them; these areas, too, have been indicated on the map as critical points of concern.

Interpretation of natural slope stability

The degree of stability of a slope is determined by a wide variety of factors; it ranges from slopes barely standing to slopes that may never fail. While the calculation of slope stability based on the engineering properties of rocks is common practice in determining stability for specific engineering projects, it would not be feasible to apply such methods on a regional scale. Therefore, some other means of appraising slope stability is desirable for a regional evaluation. The natural stability factors and an estimate of their combined influence commonly can be observed in the degree and type of landsliding present. Slopes that have failed are beyond the end of the stability spectrum, where the critical limits of control have been exceeded. Therefore, an analysis of landslides and their causes provides information from which the stability of undisturbed slopes nearby can be appraised.

The landslides in the San Clemente area are both numerous and widespread, and are believed to provide a meaningful sampling of the reasons why slopes fail by natural processes in this area. The inherent geologic features of the area and the geologic processes working toward change give some insight into the stability controls, but the introduction of man-made effects most surely will speed up or slow down the influence of these natural processes. Furthermore, natural processes commonly offer less rigorous tests of the behavior of rocks than those stresses imposed by the construction of engineering structures or other engineering works. Therefore, the slope stability characteristics presented in this study are only suggestive, and based solely on the influence of natural geology and climate. The additional effect of human agents on

Figure 4. Geomorphic features related to slope stability in the San Clemente area. Every drainage course poses a potential stability problem to the adjacent slopes through the effects of stream erosion; the drainage pattern is indicated by the broken lines. Converging drainage courses remove support from the nose of the intervening ridge leading to unstable conditions; these points are indicated by dots. The uphill slopes above landslides are potentially unstable and are shown by the arrow and arc symbol. Downhill areas subject to overriding by slide debris are shown by an arrow. These features were used in the construction of the Slope Stability Map (pl. 1).

the stability of the rocks can be calculated only when the exact location and type of engineering project has been determined.

The factors that control slope stability were observed and mapped wherever evidence was apparent at the surface. However, in most of the San Clemente area, deposits of surficial rocks, mainly slope wash, mask the nature of the bedrock geology. The distribution and nature of the various bedrock formational units and structural features below the cover could only be deduced in those masked areas, but the geomorphic features and processes were apparent from surface evidence. The high concentration of landslides, and widespread areas of probable ancient landsliding, reduce the reliability of observed attitudes of bedded rocks, so only those few attitudes believed to be reliable have been recorded on the geologic map. The elements of lithology and structure that could be observed and mapped give only a partial evaluation of their influence on slope stability. Hidden areas may pose further stability problems, once they are uncovered.

Groundwater that migrates through the various types of rock and along the contacts between them is a potential factor in landsliding. Along the sea cliffs, water seeps out along the contact between the marine terrace deposits and the underlying Capistrano Formation. Locally minor blocks of the Capistrano Formation have sloughed off below this contact. The Capistrano rocks, being for the most part poorly cemented mudstones, readily break up in water to yield a fine silt-clay mixture, but there is little field evidence to indicate that groundwater saturation has led to major sliding. However, the semi-arid climate of the region offers but few chances to observe the effects of heavy precipitation since it falls only rarely.

Certainly other geologic factors such as bedding plane weakness, and brecciation along faults and folding, affect slope stability in the area to some degree, but little or no evidence is available to appraise their influence.

CONCLUSION

Because geologic information, so vitally important in broad scale planning, seldom is available in a form that can be used directly, a geologist is commonly necessary to interpret the data. Professional geologic interpretation is especially necessary when dealing with site studies. However, only regional geologic studies enable the drawing of certain important broad interpretations, which enable the site-study geologist to build into his presentation a wider and more certain degree of interpretation. The present study of the San Clemente area is such a regional interpretation, offering a general framework of geologic conditions within which the required local site studies can be more accurately and usefully made.

It is a purpose of this study to present the slope stability data in a form directly usable for regional planning. The interpretation of slope stability control is shown on a series of maps (figs. 2, 3, and 4). Each map indicates areas or localities where geologic fe tures or processes indicate unstable or potentially u stable slopes based on either lithologic, structural, geomorphologic conditions. No absolute evaluation stability was attempted; only relative stability with the area was considered. The slope stability map (1) combines the data presented on each of the oth maps, along with additional information, to provide single analysis of the region. The map shows degr of slope stability, but because of the numerous co binations of control factors, the data are necessari generalized and give only the gross stability patte Furthermore, the map, being a composite, integra data of unequal significance into a single, interpreti scale of stability. This procedure reduces the diff ences in relative influence between stability facto and yields a map of uniform variation. The value considering the combined effect of all the fact together appears to justify any loss in precision inh ent in the construction of the map.

The presentation of the data in this manner is experiment in broad scale terrain evaluation. The p pose of this form of presentation is to aid prelimina planning of land utilization—the selection of the m feasible areas for various intended uses. From such fitting of projects to the proper terrain there shou accrue economic savings in terms of land value, m simplified engineering planning, lower construct costs, and ultimately a better and more orderly dev opment of the area. This broadscale analysis is in way intended to supplant engineering geologic stud necessary for the planning of specific engineering pr ects. To use it in such a manner would subvert purpose and lead to unwarranted conclusions.

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